LONG-TERM VARIATIONS IN NORTH–SOUTH ASYMMETRY OF SOLAR ACTIVITY

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Abstract. We present a new set of data on relative sunspot number (total, northern hemisphere, and southern hemisphere), taken for the 37-yr period 1947 to 1983; this constitutes a particularly coherent and consistent set of data, taken by the same observer (Hisako Koyama) using the same observing instrument. These data are combined with earlier data (White and Trotter, 1977) on the variation of sunspot areas for both solar hemispheres from 1874 to 1971. The combined data, covering 110 years and 10 solar cycles, are examined for periodicity in solar activity north–south asymmetry. We show that, in general, northern hemisphere activity, displayed as either An/(An + As) or Rn/(Rn + Rs), peaks about two years after sunspot minimum. This peak is greater during even cycles, pointing to a 22-yr periodicity in north–south asymmetry in solar activity, suggesting that the asymmetry is related to the 22-yr solar magnetic cycle. We demonstrate that the largest and most protracted period of northern-hemisphere activity excess in the last 110 years has occurred from 1959 to 1970; we show that there is a strong correlation between northern activity excess and a cosmic-ray density gradient perpendicular to the ecliptic plane, pointing southward, which is evident in cosmic-ray diurnal variation data from the Embudo underground cosmic-ray telescope.

1. Introduction

We present a new set of data on relative sunspot number (total, northern hemisphere, and southern hemisphere) from 1947 to 1983 (Koyama, 1985). These data are particularly valuable because this 37-yr span of data were provided by the same observer (Hisako Koyama) using the same telescope and the same method of observation. The telescope is a 20 cm refractor located in the National Science Museum in Tokyo. The solar image was projected on to a 30 cm diameter circle and sketched. Over this time period, nearly 8000 drawings of the Sun were made, and over 12 000 sunspot groups recorded. These observations have been recorded in detail and appear in published form in Koyama (1985). Figure 1 (taken from Koyama, 1985) displays the result of these observations. Figure 1(a) at the top is the well-known 'butterfly' diagram, showing the latitude distribution of sunspot groups for the period 1947–1984. Figure 1(b), shows the variation of the monthly mean of the total relative sunspot number for the period

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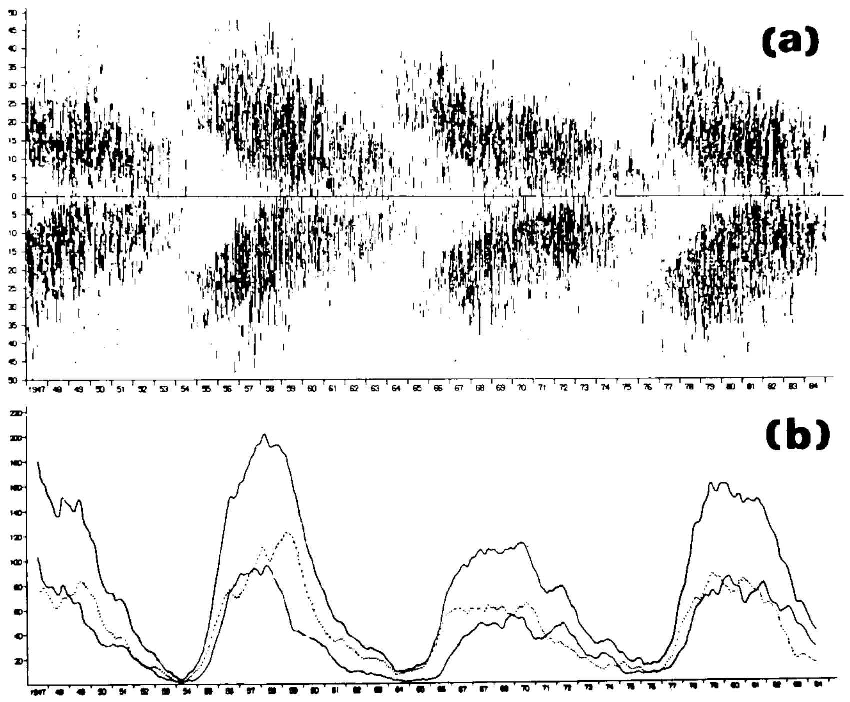

Fig. 1. (a) 'Butterfly' diagram, showing the latitude distribution of sunspot groups for the period 1947–1984. (b) Monthly mean of the total relative sunspot number for the period 1947–1984; the lower two curves show the relative numbers of northern (dotted line) and southern sunspots (solid line). Figure 1 is taken from Koyama (1985).

1947–1984; the lower two curves show the relative numbers of northern (dotted line) and southern (solid line) sunspots.

It is clear that there are large variations in both the northern and southern relative sunspot numbers, which are approximately (but not precisely) in phase with each other and with the total sunspot number, when one examines Figure 1(b) on an 11-yr time-scale. It is also clear from Figure 1(b) that there was an extended period, from 1959 to 1970, where there was significantly more activity on the Sun's northern hemisphere than on the southern hemisphere.

In this paper, we combine these data with other data on north–south asymmetry in solar activity to examine the nature of this asymmetry over a period of ten solar cycles, and we demonstrate the significance of such an asymmetry in relation to cosmic-ray density gradients in the inner heliosphere, perpendicular to the ecliptic plane.

2. North–South Asymmetry

White and Trotter (1972) have published plots of the distribution of sunspots between the north and south solar hemispheres, using data on sunspot areas from 1874 to 1971. These plots show that the largest and most obvious variation has a period of about 11 years, and that, again, north and south are approximately (but not precisely) in phase with each other, and with the total sunspot number. From these results White and Trotter (1977) have concluded that, on average, the solar magnetic cycle occurs uniformly in the north and south solar hemispheres, despite apparently random variations in the data. Roy (1977) has also examined the north–south distribution of major flares and sunspot areas, using white-light flares observed since 1859 and also 'major flares' for the period 1954 to 1975. Roy notes an asymmetry in favour of the northern hemisphere which increases strikingly with the importance of the events, and notes that the asymmetry does not appear to be connected with the 11-yr cycle or to reflect the alternating predomination of spot activity between hemispheres with a 22-yr period. The paper by Roy (1977) provides a good summary of, and references to, earlier research on the subject of north–south asymmetry in solar activity.

In Figure 2 the data of Koyama (1985) and White and Trotter (1977) are combined to examine the long-term behaviour of north–south solar activity asymmetry. Annual

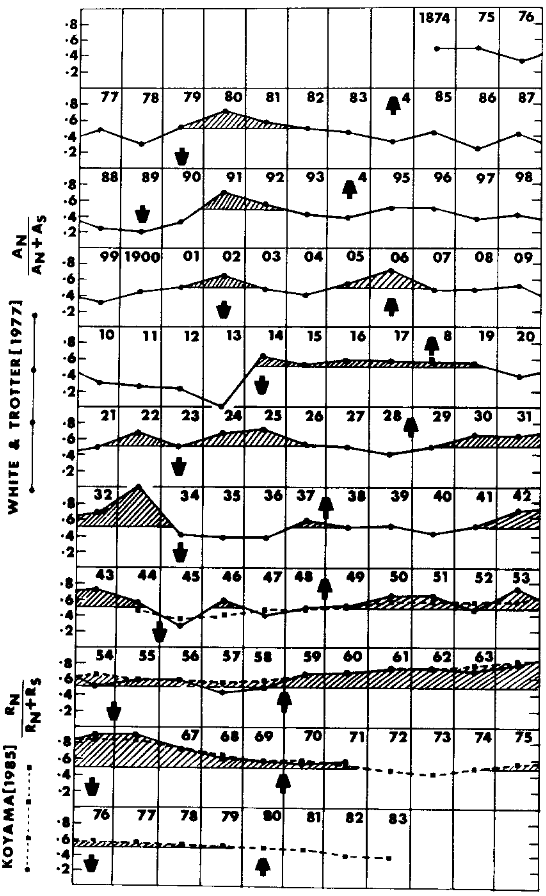

Fig. 2. North–south solar activity asymmetry expressed in terms of An/(An + As) (from White and Trotter, 1977) and in terms of Rn/(Rn + Rs) (from Koyama, 1985), from 1874 to 1983. Shading occurs when northern hemisphere activity predominates. Downward arrows indicate solar activity minima, and upward arrows indicate solar activity maxima.

values of An and As (the areas of sunspots on the northern and southern hemispheres) have been obtained from the plots of White and Trotter (1977), and the asymmetry has been plotted as circular dots joined by solid lines in Figure 2, in the form An/(An + As); when the value of this parameter exceeds 0.5 there is more activity on the Sun's northern hemisphere, as indicated by the shaded regions of Figure 2. The asymmetry from the Koyama (1985) data has been expressed in the form Rn/(Rn + Rs) (the ratio of northern to total relative sunspot number), and annual values for this parameter are displayed as squares joined by dashed lines: again, periods of excess northern activity are indicated by shading. The data from the two sources overlap from 1944 to 1971, and show a good correlation with each other, despite some differences which might be expected, bearing in mind the different nature of the asymmetry parameters. Also plotted in Figure 2 are the times of sunspot maximum and minimum, indicated by black arrows in the diagram.

Any periodicity in the north–south asymmetry seen in Figure 2 is much less apparent or pronounced than the periodicity in the activity itself, as seen for example in Figure 1(b). However, some cyclic behaviour can be noted in the north–south asymmetry. For most, though not all of the ten 11-yr periods, there is a peak in northern excess activity a year or two after solar minimum. This peaking of An/(An + As) near solar minimum has also been noted previously by Saito *et al.* (1977). In order to better demonstrate this, the data for An/(An + As) and Rn/(Rn + Rs) have been arranged in relation to each of the solar minima during the 110-yr period. In Figure 3(a) the average value for these asymmetry parameters during each solar minimum year is plotted as year 0; the average value for the year after each solar minimum is plotted as year + 1, and the average for each year before solar minimum is plotted as − 1. In this way, the data from the five years before to the five years after each solar minimum, centered on each of the ten solar minima, can be seen in Figure 3(a). There is a clear peak in excess northern activity which occurs two years after solar minimum.

When these same data are divided into even number cycles (centered on the minima of 1878.9, 1901.7, 1923.6, 1944.2, and 1964.7) and odd number cycles (centered on the minima of 1889.6, 1913.6, 1933.8, 1954.3, and 1976.5), and plotted in a similar fashion in Figure 3(b), it becomes apparent that the peak in northern excess activity two years after sunspot minimum is much more pronounced for the even cycles; there is a small peak two years after solar minimum for the odd cycle data, but it is much less pronounced than the even cycle peak. Each point in Figures 3(a) and 3(b) represents an average over 10 individual years and over 5 individual years, respectively, so the statistical accuracy is limited. In Figure 3 the standard deviation, σ, associated with the peak value is plotted on each graph; each of these values of σ is very close to the average value of σ for the other ten points in each of the three individual plots. If, for each of the three plots, an average is taken of all points except the peak year (+ 2), and this average is considered as background, then the peak values in the three plots in Figure 3 lie about 1σ, $\frac{3}{4}\sigma$, and $\frac{1}{2}\sigma$ above the corresponding background in the plots for even cycles, all data, and odd cycles, respectively.

Because of the very large northern hemisphere activity excess during the 1960's one

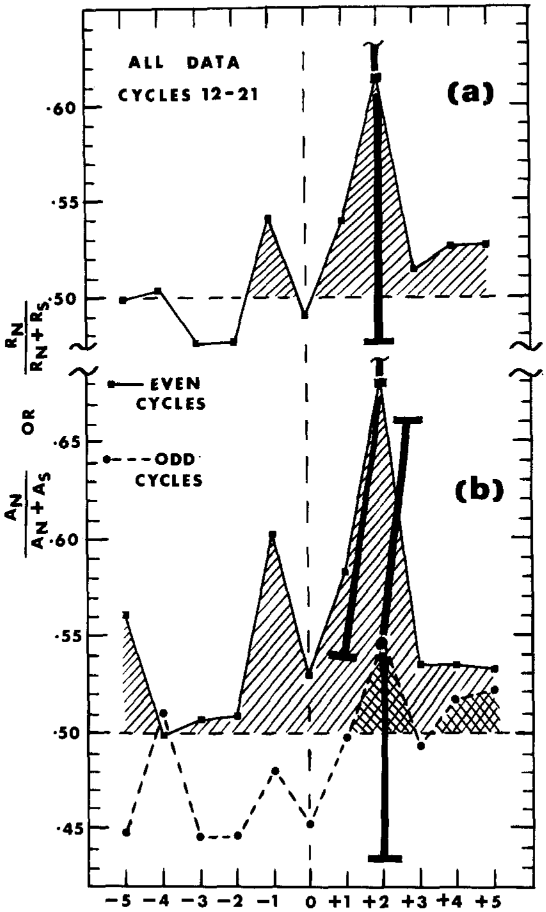

Fig. 3. North–south solar activity asymmetry expresed in terms of An/(An + As) and in terms of Rn/(Rn + Rs) from Figure 2, arranged in relation to each solar minimum during the 110-yr period. Years before solar minimum are indicated with a minus sign. (a) Contains all data, while in (b) the same data are subdivided into even cycles (squares joined with a solid line) and odd cycles (dots joined with a dashed line). In all cases, shading occurs when northern hemisphere activity predominates. The error bars indicate the standard deviation associated with the peak values.

might be tempted to ascribe the peaks in northern hemisphere activity entirely to a contribution from that decade. In order to investigate this possibility, all of the original data with the 1960's data omitted have been re-plotted in the format shown in Figure 3. The data in each of the three plots (all data, even cycles, and odd cycles) still show a peak two years after solar minimum. Without the 1960's data, the new background average value is a little lower, but the peak two years after solar minimum is slightly more significant (measured in terms of σ) for both the all-data and even-cycle plots, when compared to Figure 3 where the data for the entire 110-yr period are used; the peaks at year $+2$ are, therefore, not due to the unusual northern hemisphere activity excess of the 1960's. It is well-known that the general solar magnetic field makes a reversal in the polar caps one to two years after sunspot maximum (Howard and LaBonte, 1981). Similarly, the most flat and aligned heliospheric neutral sheet occurs one to two years after sunspot minimum (Saito, 1983), based on a careful survey of the synoptic maps of magnetic fields in the solar corona from 1958 to 1974 (Marubashi and Watanabe, 1983), maps of the solar magnetic field from 1976 to 1982 (Hoeksema, 1984), as well as the interplanetary magnetic field (IMF) polarity from cycle 17 to cycle 20 (Saito, 1972). The phase lag can also be seen in the heliomagnetic field intensity; the largest and the smallest numbers in the intensity contours appear one to two years after the sunspot maximum and minimum, respectively (Saito, 1983). The phase is a very important parameter, because the size and magnetic configuration of the heliosphere and its neutral sheet, the cosmic-ray intensity cycle, geomagnetic activity, and many other solar-terrestrial phenomena must be controlled by the heliomagnetospheric phase. In many of these cases the heliomagnetospheric phase plays the major role, with sunspot number acting as a poorer indicator of heliospheric control.

We suggest that Figure 3(b) indicates a 22-yr periodicity in north–south asymmetry in solar activity which is tied more closely with the 22-yr solar magnetic cycle than the 11-yr solar activity cycle.

3. Relation to Cosmic Radiation

Recently, Swinson *et al.* (1986) have suggested that an excess of solar activity on the Sun's northern hemisphere can be effective in excluding some of the incoming galactic cosmic radiation from the region above the ecliptic plane, leading to a south-pointing cosmic-ray density gradient perpendicular to the elciptic plane, in which there are more cosmic rays below the ecliptic plane than above it. Swinson (1970, 1976) and Hashim and Bercovitch (1972) have shown that the interaction between a gradient of cosmic-ray intensity perpendicular to the ecliptic plane ($\nabla \mathbf{N}p$) and the IMF (**B**), can give rise to a $\mathbf{B} \times \nabla \mathbf{N}p$ anisotropy of cosmic rays in the ecliptic plane which not only depends on the sense of the IMF, **B**, but changes the amplitude of the cosmic-ray diurnal variation. For a southward perpendicular cosmic-ray density gradient (higher cosmic-ray density below the ecliptic plane), when the sense of **B** is away from the Sun (A), the $\mathbf{B} \times \nabla \mathbf{N}p$ anisotropy leads to an increase in the cosmic-ray diurnal variation amplitude.

To illustrate the correlation between north–south asymmetry in solar activity and the related perpendicular cosmic-ray density gradient, data from Figure 1(b) (Koyama, 1985) from 1965 to 1983 on northern (N) and southern (S) relative sunspot numbers are replotted at the bottom of Figure 4. At the top of Figure 4 we plot the annual average cosmic-ray solar diurnal variation amplitudes for the same period; the data for each year have been split into days when the IMF, **B** was toward (T) or away from (A) the Sun. In the lower part of Figure 4 shading occurs when northern solar activity predominates over southern hemisphere solar activity; in the top of Figure 4, shading occurs when away (A) amplitudes for the cosmic-ray diurnal variation exceed toward (T) amplitudes, inferring the presence of a southward perpendicular cosmic-ray density gradient $\nabla \mathbf{N}p$. Not only is there a good general correlation between the cosmic-ray diurnal variation amplitudes with the level of solar activity, as has been noted previously by Regener and Swinson (1968), but there is also a very marked correlation between periods of excess

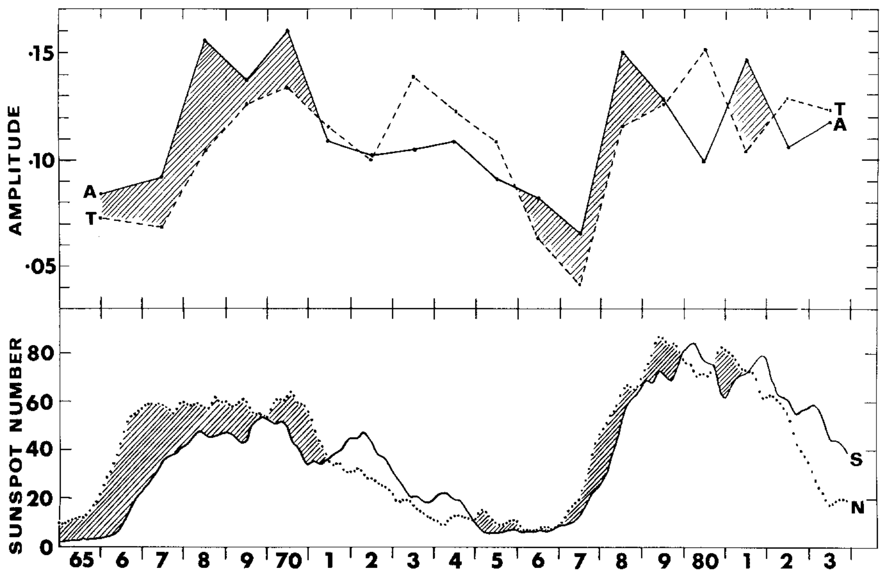

Fig. 4. *Bottom*: northern (N) and southern (S) relative sunspot number (dots and solid line, respectively), 1965 to 1983, from Koyama (1985); shading occurs when northern activity predominates. *Top*: annual average cosmic-ray solar diurnal variation amplitudes for the same period; data for each year are split into days when the IMF was toward (T) or away from (A) the Sun. Shading occurs when A-amplitudes exceed T-amplitudes, inferring the presence of a southward perpendicular cosmic-ray density gradient. Figure 4 is taken from Swinson *et al.* (1986).

northern activity on the Sun and a southward pointing cosmic-ray density gradient, as inferred from the A and T cosmic-ray diurnal variation data. A similar correlation between cosmic-ray data and a different (and shorter) set of data on north–south activity asymmetry has previously been noted by Swinson (1984). The cosmic-ray data are from the Embudo underground cosmic-ray telescope in New Mexico, which responds to primary cosmic rays whose rigidity is above 19 GV; the median rigidity for the telescope is 132 GV. Figure 4 is taken from Swinson *et al.* (1986).

4. Conclusions

We conclude that, in addition to the general 11-yr periodicity in both northern and southern hemisphere solar activity, there is also a less pronounced but still noticeable periodicity in the asymmetry in north–south activity. The northern hemisphere excess activity appears to peak about two years after sunspot minimum, and the peak is more pronounced in even numbered cycles, suggesting a 22-yr periodicity in north–south asymmetry, linking it more closely with the 22-yr heliomagnetic cycle than the 11-yr sunspot cycle. We also demonstrate that the northern hemisphere excess in solar activity asymmetry correlates strongly with a south-pointing density gradient in cosmic-ray intensity perpendicular to the ecliptic plane, inferred from cosmic-ray diurnal variation data analyzed as a function of the sense of the interplanetary magnetic field.

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